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A solution to renewable hydrogen economy for fuel cell buses – A case study for Zhangjiakou in North China

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HIGHLIGHTS

- The low electricity price is the determinant for cost reduction of electrolysis.
- The local H_2 supply shortens the delivery distance and removes the road tariff.
- The curtailed refueling price leads to a competitive bus fuel cost.
- Important events such as the Olympics are chances for the market scaling-up.
- The price mechanism is more sustainable than subsidies to attract investors.

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ABSTRACT

Fuel cell vehicles fueled with renewable hydrogen is recognized as a life-cycle carbon-free option for the transport sector, however, the profitability of the H_2 pathway becomes a key issue for the FCV commercialization. By analyzing the actual data from the Zhangjiakou fuel cell transit bus project, this research reveals it is economically feasible to commercialize FCV in areas with abundant renewable resources. Low electricity for water electrolysis, localization of H_2 supply, and curtailed end price of H_2 refueling effectively reduce the hydrogen production, delivery and refueling cost, and render a chance for the profitability of refueling stations. After the fulfillment of the intense deployment of both vehicles and hydrogen stations for the 2022 Winter Olympics, the H_2 pathway starts to make a profit thereafter. The practices in the Zhangjiakou FCB project offer a solution to the hydrogen economy, which helps to break the chicken-egg dilemma of vehicles and hydrogen infrastructure.

Introduction

Hydrogen is widely recognized as an effective energy source to reduce greenhouse gas and air pollution in the road transport sector [1–3]. Hydrogen is very versatile that it can be produced from both fossil fuels and renewable resources and utilized for many sectors through various pathways. Before hydrogen is ultimately utilized on vehicles, the hydrogen chain of

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production, storage and transport, distribution and refueling, all affect the end price of hydrogen filled into vehicles.

Oil, coal, natural gas, as well as biomass and water can be used as primary sources for H_2 production, by way of conventional methods such as by-product purified from fossil fuel processing, methane steam reforming, water electrolysis, or novel methods such as wastewater treatment and photolysis of algae [2,4,5]. Nearly 96% of the current global hydrogen is made from the hydrocarbon feedstock, and another 4% comes from water [2,5,6]. Not considering the cost of carbon capture and sequestration (CCS) which is essential for greenhouse gas abatement for fossil fuel pathways [7], hydrocarbon feedstock can render cheap hydrogen for industry applications [6,8–10]. While water electrolysis by renewable electricity is regarded as the cleanest commercial method to produce high-quality hydrogen for vehicular use, the wind- or solar-based electricity is still more expensive than the electricity generated from natural gas or coal [6,11]. The technical routes and the related investment, natural resource reserves and local energy/electricity price, etc., significantly affect the H_2 production cost [12] which could vary between USD 1.21/kg-H_2 to USD 24.0/kg-H_2 [6].

After production, various costs occur in the process of H_2 transport and refueling. Hydrogen is stored and transported to destinations in gas, liquid or solid states, through natural gas pipelines, in pressurized tanks or cryogenic super-insulated vessels, or absorbed/bounded in metal/chemical hydrides, etc. [2,4]. Practically, compressed hydrogen gas stored in containers and transported with trailers is widely used for vehicular utilization at present and liquefied hydrogen is a prospect economical way of large-scale storage and long-journey transport [5]. When hydrogen arrives at the refueling station, it is stored in the on-site cylinders in compressed gas or liquid state and filled to FCVs in the compressed gas state under different pressures [2]. The process from H_2 production to refueling is the hydrogen pathway for FCVs, which is illustrated in Fig. 1.

Different H_2 economy is represented through various pathways. Apart from the technical routes, the location of projects, the distance between H_2 sources and refueling stations, the geographical features and delivery infrastructure all influence the pathway chosen. For example, Ref. [13] used field data from the FCB bus project with "electrolysis + power-to-gas (PtG)" H_2 pathway in Rhine-Main area in Germany, and simulated the H_2 economy under different bus substitution scenarios and H_2 pathways, concluding that a decentralized PtG plant and large scale H_2 supply chain would be suitable for the area under study. According to Ref. [12], the levelized H_2 cost varies from USD 4.7/kg-H_2 (by distributed steam methane reforming) to USD 8.5/kg-H_2 (by central electrolysis with wind power and pipeline transport), with a prospect cost target of USD 2–4/kg-H_2 by distributed natural gas pathway in a mature market. However, the cost of H_2 on arrival at the refueling station does not equal the price of H_2 pumped into vehicles. Not like the industrial applications where hydrogen is usually used as direct feedstock, the FCVs need refueling stations that still have very high initial investment [14]. Generally, it takes around USD 2–3 million for one station and expected to drop to USD 1 million per station in the future [15].

Many cities in the US, Canada, EU, Japan, and China have introduced fuel cell buses to their urban transit systems to test and verify the FC technology, hydrogen economy, and emission abatement benefit. FCVs are proved technically viable with many advantages such as better energy efficiency, less pollution or emission, low noise and less smell [1,16–19]. FCVs are especially suitable for long-journey and heavy-duty transport [20] and will be comprehensively competitive as substitutes for the conventional and battery vehicles in the next two decades [21]. Despite the potentiality, the high cost during the life cycle vehicle ownership, the lack of refueling infrastructure, and less competitive H_2 end price, all hinder the adoption of FCVs [18,22,23], which in turn discourages investors to build more refueling stations or offer competitive H_2 price due to non-profitability of H_2 refueling service [24]. The positive correlation between H_2 stations and FCVs means, the scaling up of either H_2 market or vehicle market could break the chicken-egg dilemma and lead to the cost decline on both FCVs and H_2 [14,25].

However, theories of commercialization and projections for the future market do not guarantee the scaling up of the

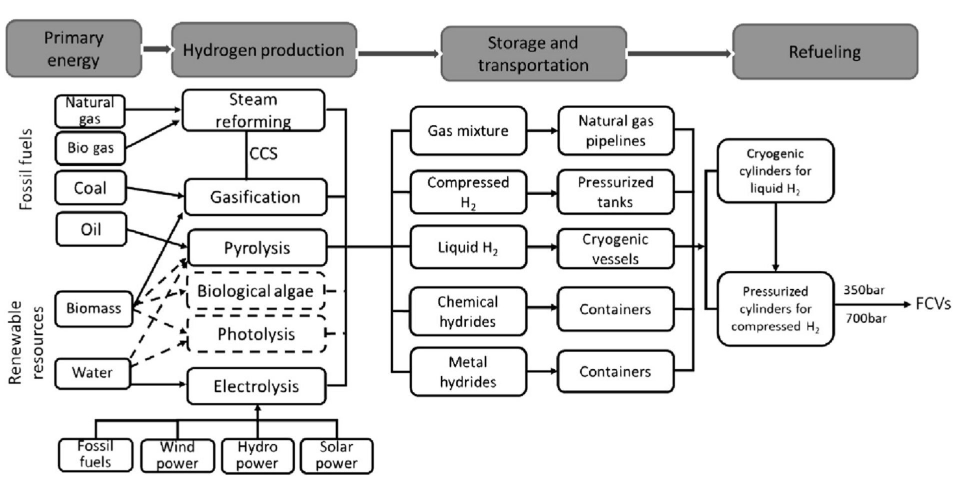

Fig. 1 – Main H_2 pathways for FCVsThe H_2 production methods in dotted lines are still under development, others are under different commercial stages, based on [2,5].

real market. Despite the technical viability of the various H_2 pathways and FCV applications, still many economic uncertainties and risks hinder the investors and operators to act. From a life cycle perspective, water electrolysis by renewable electricity is the most suitable method to render zero-carbon hydrogen for vehicles in the long run [26]. But the cost of renewable H_2 from water is very sensitive to electrolysis efficiency and the electricity price [6], and the latter one is influenced by the availability and reserves of water, wind, solar and other renewable resources and the investment of power plants and distribution grids [14,25]. Tube trailer delivery is the cheapest option for short journey transport ($\leq$50 km) due to its limited capacity, while liquid and pipeline delivery would be the options for large-volume and long-journey delivery. In addition to the H_2 states and amount delivered, the geographical context also affects the cost of delivery [15]. Though the costs of H_2 stations and FCVs are expected to decline with future deployment, the chicken-egg dilemma between H_2 infrastructure and vehicles will hardly be broken without a vision of profits.

The previous researchers have analyzed the costing details and affecting factors through the life cycle process of H_2 production to utilization. They have pointed out two methods to achieve low/no-carbon hydrogen in the long run: fossil-fuel hydrogen with CCS, and renewable hydrogen by water electrolysis. With the great uncertainty of CCS, to lower the cost of renewable hydrogen seems a practical method to try under current technology. This study aims to examine the hydrogen economy of FCVs with renewable H_2 pathway under current technology in real projects. Based on the case of transit buses in Zhangjiakou city in north China, this research provides an understanding of cost details of the hydrogen pathway and FCB operation as well as a solution to commercialize FCVs in areas with rich renewable resources.

Case in Zhangjiakou

Background of Zhangjiakou FCB project

China is a country with a mature chemical industry foundation and abundant renewable resources, but China is also a geological and geographically diverse country in natural resources and industry foundations across different areas [27]. China values hydrogen as a key option in its future energy development plan and has launched its hydrogen roadmap and ambitious plans of FCV commercial operations in its recent two "Five-Year Plans"[1] [28,29]. Thus, hydrogen and FCVs have gradually gained an industry momentum in China these years. Different regions and cities launched their hydrogen or FCV promotion plans with various H_2 pathways. As a result, the hydrogen and FCV related projects are mainly deployed around Beijing, Shanghai, Jiangxu, Guangdong, Shandong, Wuhan, Sichuan, etc., where there is rich H_2 supply from renewable resources or industrial by-products, and relatively more mature economics and industry foundation [30,31]. See Table 1.

During the early piloting phase, China mainly demonstrated FCVs in some national events and international cooperation projects, such as the 2008 Beijing Olympics, 2010 Shanghai World Expo, GEF/UNDP commercialization demonstration project and California Fuel Cell Partnership [29,32]. With these early experiences, China gradually changed its marketing focus to commercial vehicles especially buses as the breakthrough of its ambitious plan of producing 100,000 FCVs by 2030 [29,33]. Unlike the developed countries that have already demonstrated dozens of FCBs accumulatively, China has demonstrated no more than 6 buses for each of its previous programs [16]. These programs in China tested FCBs with H_2 supply from water electrolysis by grid electricity and feedstock H_2 from the chemical industry, both relied heavily on fossil fuels from the life cycle perspective considering that 60% of China's grid electricity was from coal at that time [34]. The existing H_2 pathways cannot provide life-cycle carbon-free H_2 nor a competitive H_2 price for FCBs, thus, increasing the utility of renewable electricity with low-price to produce H_2 becomes a practical way to realize both economics and zero-emission of FCB commercialization [6]. As a result, the regions with rich renewable resources become hot spots for carbon-free H_2 production and FCV deployment. Among these regions, Hebei is the first province that explicitly declared its plan of using renewable electricity to produce H_2 and has deployed fuel cell transit buses for over one year on a small-scale basis in Zhangjiakou city since September 2018 [35].

Profile of Zhangjiakou

Zhangjiakou, locates in Hebei Province, is a medium-sized city with a population of 4.43 million on an area of 38,000 km^2 within its administrative boundary [36]. Zhangjiakou also locates in the Beijing-Tianjin-Hebei zone, one of the key economic and industrial zones of China, with rich renewable resources of wind, solar, biomass and geothermal, and the city is approved by China State Council as National Renewable Energy Demonstration Zone [37]. Besides, Zhangjiakou will host the skiing events for the 2022 Winter Olympics, which pick low-carbon as the option of the Games [38]. Zhangjiakou thus becomes a prospective hydrogen city in northern China.

FC transit bus service and its H_2 pathway

From October 2018 to October 2019, accumulatively 74 fuel cell transit buses have experienced a full year public transit service in Zhangjiakou city [35]. The main parameters of these buses are listed in Table 2.

All these buses are fuel cell and battery hybrids from two Chinese domestic manufacturers. 33 Foton buses with another 13 standbys have been operated on Route 23 and 33 since Sept. 2018; 24 Yutong buses with 1 more standby have been operated on Route 1 since Oct. 2018. The single trip distance of Route 23, 33, and 1 is respectively 14 km, 10 km, and 10 km, with similar route conditions across the main city. These buses have been refueled at the same hydrogen refueling station which is respectively 2 km, 4 km, and 5 km away from one terminal of the route 23, 33, and 1. See Fig. 2.

[1] The Five-Year Plans are a series of national plans of the overall development of China. 2011–2015 and 2016–2020 are respectively the 12th and 13th Five-Years.

Table 1 – The main Hydrogen industry regions and FCV demonstrations in China.

Regions	Typical cities or provinces	Resources for H_2 supply	Number of FCVs	Number of refueling stations	
				Opened	Planned to open by 2020
North	Beijing, Hebei, Liaoning	Wind, solar, coal	219	3	30
East	Shanghai, Jiangsu, Shandong	Industrial by-product H_2, offshore wind, nuclear power	563	8	50
West	Sichuan	Hydropower, biogas, natural gas	40	1	5
South	Foshan, Yunfu	Industrial by-product H_2	95	7	40
Middle	Hubei, Henan	Hydropower, coal	43	4	21

Source: Ref. [27,30].

Table 2 – Fuel cell transit buses in Zhangjiakou.

	Bus route 23,33	Bus route 1
Number of buses[a]	33 scheduled +13 standbys	24 scheduled +1 standby
Service start time	Sept. 2018	Oct. 2018
Bus manufacturer	Foton	Yutong
Bus length	10.5m	12m
Fuel cell power	30 kW	60 kW
Battery capacity	83kWh	108kWh
Curb weight	12,500 Kg	12,900 Kg
H_2 tank pressure	35Mpa	35Mpa
Hydrogen capacity	19.2 kg	25.6 kg

[a] According to the bus operating agency, 3 buses were used as commuting buses for drivers, only 71 buses had been run on public routes during that time.

The star in the map refers to the temporary refueling station. The dotted line in each map from the left to the right is Route 23, 33, and 1.

Fig. 2 – The location of FCB service and the refueling station.

However, this refueling station is a temporary one for the initial stage of the Zhangjiakou Project. The daily refueling capacity is 1500 kg under the pressure of 350bar with 3 dispensers. The construction fee of the station is 12,000,000 RMB and the annual labor fee is around 1,450,000 RMB for 26 staff.

The designed H_2 pathway for Zhangjiakou is centralized water electrolysis by renewable electricity in the H_2 plant of Wangshan Recycling Economics Demonstration Zone, which locates in the Dacanggai Town of Qiaodong District, around 10 km east of the city center. The H_2 plant will be constructed with 2 phases. Phase 1 has an annual H_2 production capacity of 1400 tons and the daily distribution capacity is 2 tons. Phase 2 will increase the annual production capacity to 7100 tons with an on-site wind power plant. Phase 1 will supply H_2 from the mid of 2020 and Phase 2 from the mid of 2021. The H_2 for the 74 transit buses already on road was made off-site from fossil fuels and delivered by tube trailers and refueled at a subsidized end price of 35 RMB/kg.

Policy incentives and local planning

China offers FCB purchasing subsidy amount to 500,000 RMB to each new registered bus until March 26, 2019, and 400,000 RMB from March 26, 2019 to June 25, 2019, but unclear amount thereafter [39]. Thus, the 74 buses operating on Zhangjiakou public routes since October 2018 can obtain 500,000 RMB fiscal subsidy for each bus. Though the future purchasing subsidy for FCB is unclear for the years after 2020, the phase-down trend of financial subsidy for purchasing NEVs has been determined in China that the purchasing subsidy from the central government will be gradually decreased. Moreover, from 2019, the purchasing subsidy for FCBs will be granted by two payments until the buses have fulfilled 20,000 km service on road [40]. However, the local governments can keep on providing purchasing subsidies for transit buses instead of other vehicle models. In the meantime, the balanced operation rewards for diesel transit buses[2] and the planned-to-cease purchasing subsidies for other models will be shifted to be operation rewards for new energy transit buses [41].

The H_2 refueling station with a capacity above 200 kg/day used to be granted 4 million RMB national subsidy for construction during 2013–2015. Hebei promised to grant a modest subsidy for H_2 station construction from Aug. 2019 without clearly stating the amount [42]. The future incentive for H_2 infrastructure will be shifted from construction to operation [40]. In the provincial plan, the FCVs on-road will respectively reach 2,500, 10,000 and 50,000 by the year 2022, 2025 and 2030; and the H_2 stations will be 20, 50 and 100 by the same years [42].

Zhangjiakou was also listed in the first batch of Public Transport cities of the 13th Five-year [43]. According to the city construction requirement, by the end of 2020, at least 35% of the transit buses should be new energy ones; with 5 years construction, the public transport share ratio should increase from 10% to 16% [44], among which 60% should be green options in the entire city and 100% green in the main urban areas and Chongli district [45].

Method and data

Methodology

This research adopts the life cycle inventory analysis (LCI) in ISO14040, that the input and output data about the H_2 pathway and FCB operation are compiled and studied [46]. The life cycle perspective in this research refers to the process of H_2 flow, rather than the manufacturing chain involved in the entire H_2 and fuel cell industry. This research also references Ref. [6,17,18] to build the costing parameters of the H_2 pathway and FCB operation as shown in Fig. 3, and uses a bottom-up approach to gather the actual data of each phase of Zhangjiakou FCB project.

The following four equations are used to calculate the LCC of the FCB operation in Zhangjiakou.

$$C_{lcc} = N_{bus}\left(C_{pur} - B_{sub}\right) + C_{op} \tag{1}$$

Eq. (1) describes the life cycle cost of the FC transit bus fleet (C_{lcc}), including the initial capital investment (bus purchasing fee (C_{pur}), purchasing subsidy (B_{sub})) and fleet operation cost (C_{op}). N_{bus} is the number of buses in the fleet.

$$C_{op} = \sum_{j=0}\left(N_{bus}\left(D_j C_h + C_{mab} - B_{opb}\right)\right) \tag{2}$$

Eq. (2) describes the fleet operation cost (C_{op}), where D_j is the annual driven distance, C_h is the H_2 cost per driven distance, C_{mab} is the annual maintenance cost of one bus, B_{opb} is the assumed annual benefits of operation subsidy or incentives per bus.

$$C_p = C_{h-pr} + C_{h-tran} + C_{sta} \tag{3}$$

Eq. (3) describes the H_2 end price for refueling (C_p), including the H_2 production cost (C_{h-pr}), transport cost (C_{h-tran}), and refueling station cost (C_{sta}) which is calculated in Eq. (4), where N_{sta-j} is the annual number of refueling stations, C_{con} and B_{con} respectively is the construction cost and subsidy of a station, C_{la} is the labor cost of a station, C_{mah} is the maintenance cost of a station, and B_{oph} is the potential operation incentives for a station.

$$C_{sta} = \sum_{j=o}\left(N_{sta-j}\left(C_{con} - B_{con} + C_{la} + C_{mah} - B_{oph}\right)\right) \tag{4}$$

Scenarios and assumptions

The introduction of the Zhangjiakou case inputs the data for the scenarios and assumptions below.

FC transit bus and H_2 station scenarios

The numbers of FC transit buses and H_2 stations are projected according to the milestones in the local plans [47,48] and extrapolated within different timeframes, see Table 3.

Data and assumptions

There are some assumptions for the costing data of H_2 pathway and FCB operation for Zhangjiakou project:

- All costs and prices are in current (Year 2020) prices in Chinese RMB (1USD ≈ 7RMB);
- The system electrolysis efficiency (AC) is 55 kWh/kg-H_2 on an average at present in China and will reduce to 50 kWh-H_2 according to the main domestic electrolysis system suppliers;
- The renewable electricity price for water electrolysis is 0.15 RMB/kWh in Zhangjiakou [49];

[2] There is an energy-saving reward for diesel buses if they can save certain amount of diesel each fiscal year.

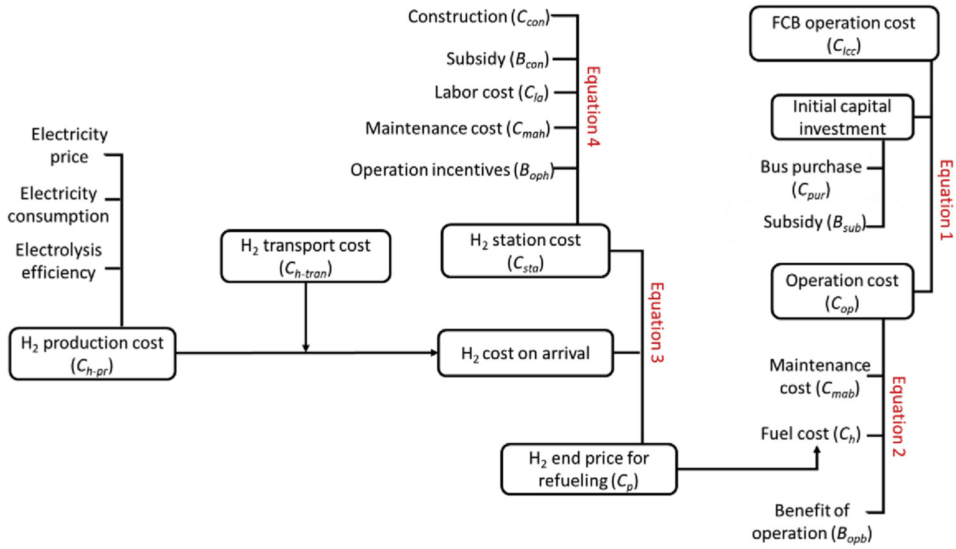

Fig. 3 – The costing data of H_2 pathway and FCB operation in Zhangjiakou.

Table 3 – Fuel cell transit bus and H_2 station projection.

Year	2018	2019	2020	2021	2022	2025	2030	2035
Number of FC transit buses	74	354	444	994	1040	1220	1510	1760
Number of H_2 stations[a]	1	1	9	20	21	25	31	36

[a] The H_2 stations extrapolated here are only for transit buses, not considering the needs for other vehicle models. The numbers of H_2 stations in 2018–2019 are actual data.

- Water price is 7.35 RMB/ton, and 1Nm^3 H_2 production needs 1.5L water;
- One trailer can effectively transport 300 kg H_2 each time under 200 bar at present, and 450 kg under 300bar from 2021 to 800 kg under 500 bar from 2026;
- The average transport distance of a trailer is 300 km per day when H_2 comes from Hebei by-product sources and 40 km per day when local supply is ready from the late half of 2020;
- The construction cost of refueling stations excludes the land acquisition, which value is specific according to the land property in each case in China;
- A refueling station with 1000 kg capacity needs construction fee of 1,800,000 RMB in 2019 and decreases to 1,000,000 RMB since 2028, and the service life of the H_2 refueling station is 15 years;
- The construction subsidy is assumed to be 30% value of the equipment investment during 2020–2025 and 20% value of the equipment investment during 2026–2030; the equipment investment is 9,000,000 RMB for each station in 2019 and decreases by 10% each year until it reaches 5,000,000 RMB;
- Each station needs 26 staff with an annual payment of 54,000 RMB in 2019, the payment will increase by a yearly rate of 5% and the staff number will reduce to be 10;
- All transit buses are assumed to be 12m for calculation, and the purchasing price for each bus is 3,000,000 RMB in 2018 and decreases by 10% each year until the price reaches 800,000 RMB[3]; the potential purchasing subsidies is 400,000 RMB in 2019 and decreases by an annual 80,000 RMB until 0 in 2025;
- The bus life is 10 years and the salvage value of the buses is 0 at the end of the bus life; the total maintenance cost is 10% of the purchasing fee;
- The fuel economy of the FCB is 8 kg-H_2/100 km in 2019, and it will reduce to 5 kg-H_2/100 km in 2035. The bus daily mileage is 220 km.

Based on the scenarios and assumptions above, the key parameters for the LCC calculation are listed in Table 4.

Results and discussion

Costing structure of H_2 pathway

The costing structure of the H_2 pathway mainly involves the H_2 production (electrolysis), transport and refueling. Zhangjiakou sets a curtailed refueling price for transit buses, that it takes 35 RMB/kg at present, and the target refueling price for transit buses will be 30 RMB/kg during 2026–2030, and 25 RMB/kg during 2031–2035. Fig. 4 shows that the year 2022 is the turning point of the H_2 pathway cost because of the large scale of bus operation and H_2 station deployment before the Winter Olympics. The end cost of H_2 for transit buses will reduce to 17.82 RMB/kg in 2022, much cheaper than the curtailed price

[3] An average price for a 12m CNG bus in China.

Table 4 – Key parameters for the LCC calculation.

Year	2020	2021	2022	2025	2030	2035
Electrolysis efficiency (AC)	55kWh/kg-H_2	54.5kWh/kg-H_2	54kWh/kg-H_2	52.5kWh/kg-H_2	50kWh/kg-H_2	50kWh/kg-H_2
Trailer pressure	200bar	300bar	300bar	300bar	500bar	500bar
Storage capacity per trailer	300 kg	450 kg	450 kg	450 kg	800 kg	800 kg
Average daily distance of transport per trailer	170 km	40 km	40 km	40 km	40 km	40 km
Construction fee for H_2 station (RMB)	1800	1700	1600	1300	1000	1000
Equipment fee (RMB) and subsidy ratio	900; 30%	810; 30%	729; 30%	531; 30%	500; 20%	500; 0%
Station labor annual payment (RMB) and staff number	60,000;26	63,000;22	66,000;18	76,000;14	97,000;10	124,000;10
FCB purchasing fee and subsidy (RMB)	2,430,000;400,000	2,190,000;320,000	1,970,000;240,000	1,430,000;0	850,000;0	800,000;0
Fuel economy (kg-H_2/100 km)	8	7.8	7.6	7	6	5
Target H_2 selling price for refueling (RMB)	35	35	35	35	30	25

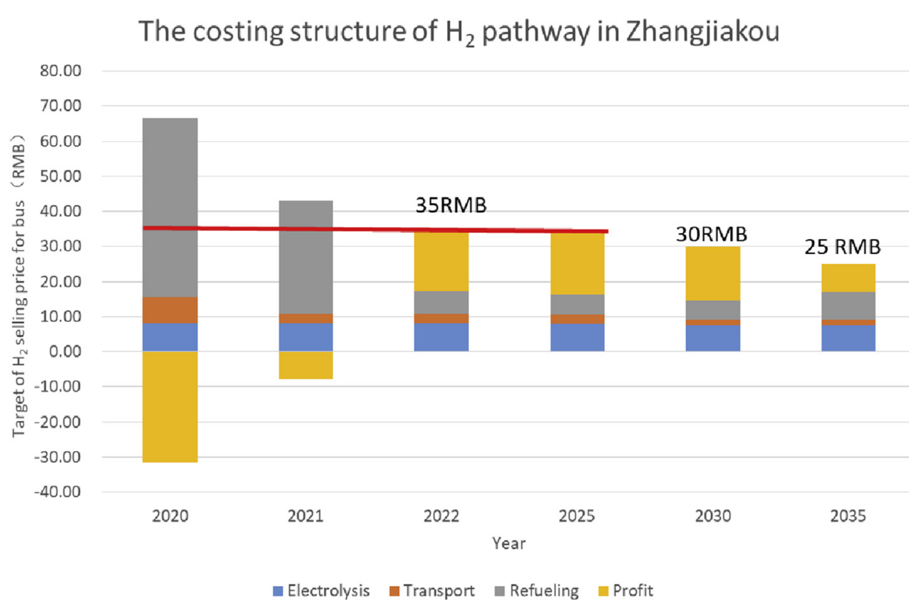

Fig. 4 – The costing structure of H_2 pathway in Zhangjiakou.

of 35 RMB/kg. However, as the incremental transit buses and refueling stations have been put into service mainly during 2019–2022, the cost of the H_2 pathway during that period is much higher than the curtailed selling price, reaching its peak of 66.62 RMB/kg in 2020. As a result, the H_2 pathway system in the Zhangjiakou transit bus project has to bear years of deficit before it starts to make profits. The profit of the H_2 pathway during 2022–2025 is higher than that in the later years, as high as 18.7 RMB/kg can be earned in 2025. The profit goes down with the reduction of curtailed selling price and the maturity of technology and market, that during 2031–2035 the profit reduces to 8.03 RMB/kg-H_2 in 2035.

From 2022, the costing structure of the H_2 pathway will maintain relatively stable during each planning timeframe. The electrolysis system (AC) cost will be the lowest of 7.5 RMB/kg-H_2 in 2030, in which year the system efficiency will reach its technology maximum. The H_2 transport system takes the smallest share of the pathway cost, that it will need 2.72–2.74 RMB for 1 kg H_2 carried by trailers with 300 bar vessels during 2022–2025, and 1.53–1.57 RMB/kg under 500 bar from 2026. As for refueling, the cost trend is different from the previous two sectors, that it will rise to 5.7–7.55 RMB/kg-H_2 during 2022–2025, then reduce to 4.68–6.52 RMB/kg during 2026–2030, and increase again to 6.01–7.9 RMB/kg during 2031–2035.

Costing details of different sectors of the H_2 pathway

H_2 production

H_2 production cost is mainly related to the electrolysis efficiency and electricity price in Zhangjiakou. As the electricity price is stable for the Zhangjiakou project, the cost will reduce with efficiency improvement. But the improvement of electrolysis efficiency is minor due to the technology bound, that only 0.75 RMB/kg-H_2 can be reduced for the direct cost of water electrolysis in Zhangjiakou in the next 10 years. The treatment cost of water before electrolysis and the purification cost of output gas is counted in the electrolysis system (AC) efficiency. When the electrolysis efficiency reaches its technology upper limit in 2030, it still needs 50kWh valuing 7.5 RMB for 1 kg H_2 production in the electrolysis system (AC).

The water cost in this research is only 0.01RMB/kg-H_2 according to the water price in Zhangjiakou and water consumption in the real project. As a result, the direct cost of electrolysis becomes the main factor affecting the cost of H_2 production in the Zhangjiakou project. Due to the limited room for electrolysis efficiency improvement, the electricity price is the determinant of the direct cost of H_2 production. When the electricity price reduces by every 0.01RMB/kWh, the direct cost for electrolysis could reduce by 0.5–0.55RMB/kg-H_2. As the fluctuation in electricity price has 50 times impact on the electrolysis cost, reducing the electricity price is the key to reduce renewable H_2 production cost.

This result is consistent with previous research that the total cost of renewable hydrogen production is very sensitive to electricity price rather than water price, electrolysis efficiency or plant life [3], and using low price electricity is a key for renewable H_2 economy in China [6].

H_2 transport

As for the H_2 transport, several factors could influence the H_2 price on arrival at the refueling station: the road tariff, fuel cost, and the trailer fleet operation cost (test and insurance, maintenance and labor). This research does not count the purchasing cost of trailers and vessels into the H_2 transport sector, as it is the H_2 producer's responsibility to deliver the gas to the destinations and they usually hire trailers from the trailer owners, who usually charge their customers by the fees listed above.

We already know that delivery distance and vessel capacity are two factors for trailer transport costs. From the year 2021, the H_2 for refueling will be totally from the Wangshan H_2 plant. The round-trip distance between the H_2 plant and refueling stations will reduce from 300 km to averagely 40 km across the city. In the meantime, the vessel pressure will increase from 200 bar to 300 bar. From 2026, only vessel pressure will increase to 500 bar.

In Fig. 5, the delivery cost hugely reduces in 2021 and 2026 when distance or pressure changes. While vessel pressure increase brings an equally 44% cost reduction on trailer fuel cost and the fleet operation cost in 2026, distance affects road tariff and fuel cost more than the fleet operation cost in 2021, in which year 90% road tariff and fuel cost reduces and only 36% trailer fleet cost reduce. The localization of H_2 supply not only shortens the delivery distance but also induces no inner-city road tariff which otherwise would be a big sum across cities in China.

Besides, among the trailer fleet costs, labor cost for drivers is the biggest part and takes more than half the proportion of the total fleet cost compared with the cost of trailer insurance, test, and maintenance. The trailer fleet cost is closely related to trailer numbers in the fleet. From 2026, distance and vessel pressure will have no change in Zhangjiakou that more trailers will be needed when more H_2 needs to be delivered, which will induce more trailer fleet costs. Thus, technology improvement on liquefied H_2 or pipeline delivery would bring cost efficiency for larger volume and longer distance delivery, especially when Zhangjiakou starts to sell H_2 to Beijing and other nearby cities.

H_2 refueling

The refueling cost refers to the cost occurs in the H_2 refueling station, including the initial capital investment of the station, on-site equipment maintenance, labor, and station subsidies. The station has 15 years' life, and the newly built stations are intensively deployed before 2022 for the Winter Olympics. From 2022, there will be only 1–2 new stations built each year, thus, the refueling cost lies heavily in the first two years because of the huge initial capital investment. In 2020 and 2021, respectively 8 and 11 new stations will be built. Each station can be granted a sum of subsidy valuing 30% of equipment investment from 2020 to 2025.

Not considering the subsidy, from 2020 to 2035, the capital investment share reduces from 87% to 18%, while the labor-cost share increases from 9% to 81%, as Fig. 6 shows. The equipment maintenance keeps at a low ratio in the cost structure. While the cost structure experience such a big change, the absolute value of annual equipment maintenance and annual labor cost do not change much through these 15 years. The intensive deployment of H_2 stations before the 2022 Winter Olympics brings huge capital investment for the total refueling cost.

Life cycle cost of FCB operation

The transit bus operators have to purchase the FCBs, repair and maintain the buses and pay for the H_2 refueled. No matter what is the economy of the H_2 pathway, the H_2 is sold at a curtailed price for public service in Zhangjiakou. This price separates the economy of the H_2 pathway from FCB operation. On one hand, the H_2 production sector, delivery

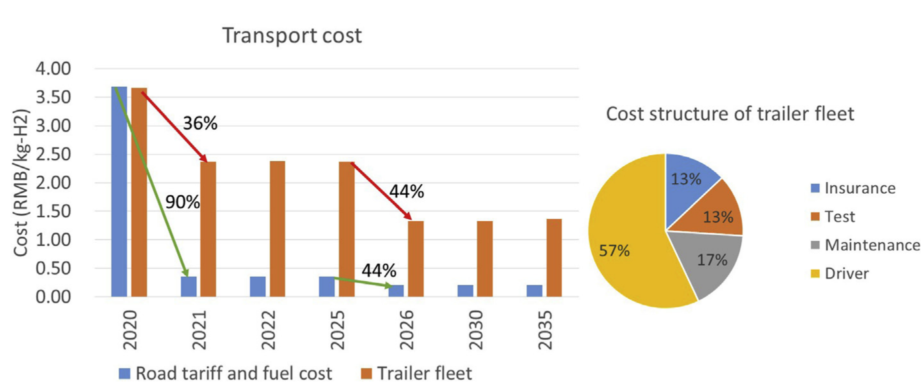

Fig. 5 – Main transport cost trend (left) and cost structure of the trailer fleet (right).

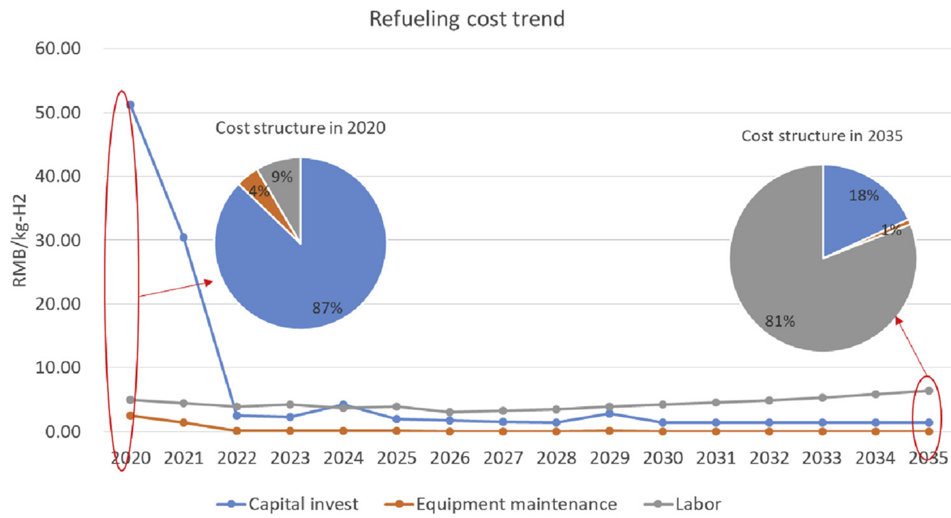

Fig. 6 – Refueling cost structure and trend.

sector, and refueling stations have to reduce their own cost with better technology and management, to make profits from this price; on the other, the transit bus services are guaranteed a reasonable or even competitive fuel price in case the H_2 sectors shift their own cost to transit bus operators. This research does not consider the common costs as diesel bus services, such as driver payment, fleet management, ticket profits, etc.

At present, the capital investment is the largest part of the cost of transit bus operation. It takes 2.5 million RMB after deducting the subsidy to purchase one 12m FCB. The next 10 years will be the market scaling up phase of FCBs in China and the target price for one 12m FCB is 800,000 RMB, which is the average price of a 12m Diesel bus. Besides, the fuel cost of one fuel cell transit bus will reduce from 2.80 RMB/km in 2020 to 1.25 RMB/km in 2035, while the present fuel cost of diesel buses whose fuel economy is around 49.97L/100 km [50] is 2.56 RMB/km[4]. The curtailed H_2 selling price for transit buses guarantees the competitiveness of the FCB fuel cost even when diesel price reduces sharply in March 2020.

There is another benefit of FCB operation. Assuming that the direct CO_2 emission of 12m transit buses is 125.72 kg/100 km per bus [50] and the newly deployed FCBs are all substitutes for diesel buses, the FC transit bus project in Zhangjiakou can reduce respectively 4421 tons CO_2 in 2020 and 17,524 tons CO_2 in 2035. The carbon emission reduction could turn into profit when the carbon trading scheme begins to work in China nationwide after 2020. According to the trial carbon trading in 7 pilot cities or provinces in China during 2013–2018, the average nationwide carbon price was 14 RMB/ton which was yet very low [51,52]. Then the FCB operation can gather at least another 61,892 RMB and 170,066 RMB value of carbon profit respectively in 2020 and 2025.

[4] The vehicular diesel price reduced to 5.13RMB/L in Beijing on the day of 23 March 2020 due to the coronavirus and global oil price jump.

Conclusion

This research adopts the life cycle inventory method to analyze the costing details of H_2 pathway and FCB operation in Zhangjiakou transit bus system, verifies the economic feasibility of H_2 pathway based on water electrolysis by renewable electricity, and reveals the key issues for future cost reduction for large scale commercialization of FCBs in the northern part of China where there are rich solar and wind power resources.

With a curtailed electricity price in Zhangjiakou, the direct cost of water electrolysis can be reduced to 7.5 RMB/kg-H_2 from 2030, which is the key to reduce H_2 production cost. With the electricity pricing mechanism and large scale of the electricity storage system, the case in Zhangjiakou offers the potentiality to achieve an average low price of water electrolysis from green electricity nationwide [6], not just in cities with wind/solar power plants.

In Zhangjiakou, the localization of H_2 supply guarantees the economy of trailer transport. It effectively reduces both road tariffs and fuel costs of delivery. However, to achieve long term profitability of large-scale delivery and storage, technology improvements such as vessel pressure increase and the liquid pathway should also be considered in later years. With hydrogen market scaling up around the Beijing-Tianjin-Hebei area, pipeline delivery should be studied for long-journey transport of H_2 produced in Zhangjiakou, considering the highways across northern cities are often closed in snow season.

As for the refueling station, because of the huge initial capital investment, it is difficult for station operators to make a profit in the initial years, even with station construction subsidy. As H_2 is sold at a curtailed price in Zhangjiakou, the profit is limited within the price boundary, thus, subsidy for refueling operation according to the amount of H_2 refueled is important for the profitability of the station operators. With the increasing business scale of FCBs on road, the station operators can make profits in the long term. Then, to guarantee the continuity of refueling business for the station constructors such as “franchise right of operation” would be beneficial to attract initial investment, which could only be paid back after many years of business until the vehicles on road reach enough scale.

On the contrary, curtailed H_2 end price is welcomed by FCB operators, as it helps to reduce the fuel cost of the bus operation. The cost of the FCB fleet service also lies heavily in the initial investment. Despite the bus purchasing subsidy and the competitive fuel economy, the life cycle cost of the FCBs will continue to be more expensive than the diesel ones in the next 10 years. The coming CO_2 trading scheme will be a remedy for such a big investment. A reasonable expectation of the future carbon price would be 1000–2000 RMB/ton [53], which could be very attractive for bus operators to gradually phase out their diesel buses. However, the most important benefit of FCB operation is not the monetary feedback directly from carbon sales which have been uncertain yet, but the social benefits from the environment, as well as the potential disincentives such as road limit that could cause inconvenience to diesel buses on road.

Zhangjiakou FC transit bus service not only verified the competence of hydrogen and fuel cell technology for the transport sector in cold areas in northern China but also verified the profitability of the H_2 pathway in the long run through the process of H_2 production, transport, and refueling. Though the calculation of the costing details was based on assumptions and only transit buses were considered, the FC transit bus project in Zhangjiakou offered a cost detail in each sector and proved that low electricity price, localization of H_2 supply and curtailed end price of refueling could be a solution for renewable H_2 economy in a long run. Generally, when the local H_2 plant opens, the H_2 pathway cost mainly lies in the sectors of water electrolysis and refueling. So the selling price of renewable electricity and the end price of H_2 refueling are the most important factors for the long-term profitability of the Zhangjiakou project.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2020.03.206.

REFERENCES

[1] Liu F, et al. The impact of fuel cell vehicle deployment on road transport greenhouse gas emissions: the China case. Int J Hydrogen Energy 2018;43(50):22604–21.

[2] Salvi BL, Subramanian KA. Sustainable development of road transportation sector using hydrogen energy system. Renew Sustain Energy Rev 2015;51:1132–55.

[3] Liu H, et al. Analysis of Ontario's hydrogen economy demands from hydrogen fuel cell vehicles. Int J Hydrogen Energy 2012;37(11):8905–16.

[4] Dutta S. A review on production, storage of hydrogen and its utilization as an energy resource. J Ind Eng Chem 2014;20(4):1148–56.

[5] Apostolou D, Xydis G. A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects. Renew Sustain Energy Rev 2019;113:109292.

[6] Li Y, et al. Life cycle cost and sensitivity analysis of a hydrogen system using low-price electricity in China. Int J Hydrogen Energy 2017;42(4):1899–911.

[7] Verma A, Olateju B, Kumar A. Greenhouse gas abatement costs of hydrogen production from underground coal gasification. Energy 2015;85:556–68.

[8] Chisalita D-A, Cormos C-C. Techno-economic assessment of hydrogen production processes based on various natural gas chemical looping systems with carbon capture. Energy 2019;181:331–44.

[9] Cormos A-M, Cormos C-C. Techno-economic assessment of combined hydrogen & power co-generation with carbon capture: the case of coal gasification. Appl Therm Eng 2019;147:29–39.

[10] Szima S, Cormos C-C. Techno – economic assessment of flexible decarbonized hydrogen and power co-production based on natural gas dry reforming. Int J Hydrogen Energy 2019;44(60):31712–23.

[11] Granovskii M, Dincer I, Rosen MA. Greenhouse gas emissions reduction by use of wind and solar energies for hydrogen and electricity production: economic factors. Int J Hydrogen Energy 2007;32(8):927–31.

[12] Moliner R, Lázaro MJ, Suelves I. Analysis of the strategies for bridging the gap towards the Hydrogen Economy. Int J Hydrogen Energy 2016;41(43):19500–8.

[13] Coleman D, et al. The value chain of green hydrogen for fuel cell buses – a case study for the Rhine-Main area in Germany. Int J Hydrogen Energy 2019;48(8):5122–33.

[14] Iordache I, Schitea D, Iordache M. Hydrogen refueling station infrastructure roll-up, an indicative assessment of the commercial viability and profitability. Int J Hydrogen Energy 2017;42(8):4721–32.

[15] Tlili O, et al. Hydrogen market penetration feasibility assessment: mobility and natural gas markets in the US, Europe, China and Japan. Int J Hydrogen Energy 2019;44(31):16048–68.

[16] Hua T, et al. Status of hydrogen fuel cell electric buses worldwide. J Power Sources 2014;269:975–93.

[17] Lajunen A, Lipman T. Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. Energy 2016;106:329–42.

[18] Ally J, Pryor T. Life cycle costing of diesel, natural gas, hybrid and hydrogen fuel cell bus systems: an Australian case study. Energy Pol 2016;94:285–94.

[19] Itaoka K, Saito A, Sasaki K. Public perception on hydrogen infrastructure in Japan: influence of rollout of commercial fuel cell vehicles. Int J Hydrogen Energy 2017;42(11):7290–6.

[20] Shin J, Hwang W-S, Choi H. Can hydrogen fuel vehicles be a sustainable alternative on vehicle market?: comparison of electric and hydrogen fuel cell vehicles. Technol Forecast Soc Change 2019;143:239–48.

[21] Tanç B, et al. Overview of the next quarter century vision of hydrogen fuel cell electric vehicles. Int J Hydrogen Energy 2019;44(20):10120–8.

[22] Wang J. Barriers of scaling-up fuel cells: cost, durability and reliability. Energy 2015;80:509–21.

[23] Lipman TE, Elke M, Lidicker J. Hydrogen fuel cell electric vehicle performance and user-response assessment: results

of an extended driver study. Int J Hydrogen Energy 2018;43(27):12442–54.
[24] Engelen P-J, Kool C, Li Y. A barrier options approach to modeling project failure: the case of hydrogen fuel infrastructure. Resour Energy Econ 2016;43:33–56.
[25] Hydrogen Council. Path to hydrogen competitiveness A cost perspective. 2020.
[26] Navas-Anguita Z, et al. Prospective techno-economic and environmental assessment of a national hydrogen production mix for road transport. Appl Energy 2020;259:114121.
[27] Lu J, et al. Building the hydrogen economy in China: drivers, resources and technologies. Renew Sustain Energy Rev 2013;23:543–56.
[28] Kendall M. Fuel cell development for New Energy Vehicles (NEVs) and clean air in China. Prog Nat Sci Mater Int 2018;28(2):113–20.
[29] Han W, et al. Demonstrations and marketing strategies of hydrogen fuel cell vehicles in China. Int J Hydrogen Energy 2014;39(25):13859–72.
[30] China Hydrogen Alliance. China hydrogen and fuel cell industry white book. 2019. p. 1–62.
[31] Tian M-W, et al. The multiple selections of fostering applications of hydrogen energy by integrating economic and industrial evaluation of different regions. Int J Hydrogen Energy 2019;44(56):29390–8.
[32] Yuan K, Lin W. Hydrogen in China: policy, program and progress. Int J Hydrogen Energy 2010;35(7):3110–3.
[33] Zhongfu T, et al. Focus on fuel cell systems in China. Renew Sustain Energy Rev 2015;47:912–23.
[34] National Energy Administration of China. National power industry Statistics for 2018. 18 January 2019. Available from: http://www.nea.gov.cn/2019-01/18/c_137754977.htm.
[35] Ma M. 174 fuel cell buses operated in Zhangjiakou. Zhangjiakou News; 2019.
[36] Zhangjiakou municipal statistics agency. 2018 Bulletin of Zhangjiakou economic and social development. Zhangjiakou news; 2019.
[37] International Renewable Energy Agency. Zhangjiakou energy transformation strategy 2050. 2019.
[38] International Renewable Energy Agency. IRENA to help deliver low-carbon 2022 winter Olympics in Zhangjiakou. 2018. China.
[39] Ministry of Finance. Circular on further perfecting fiscal subsidy for the promotion of New Energy vehicles. 2019 [China].
[40] Chai X. Decrease the NEV fiscal subsidy to promote the fittest. China Financial and Economics News; 2019.
[41] Zeng J. Substituting subsidies with rewards to support new energy buses operation from 2020. Economic Daily; 2019.
[42] Industry and Information technology Department of Hebei Province. In: The Development and Implementation of the hydrogen-energy Industry in Hebei Province E.a.I. Department; 2019. Hebei.
[43] MOT circular of the first batch of cities to be established in promoting the construction of public transport cities during the 13th “Five-year plan”, M.o. Transport; 2017. People's Republic of China.
[44] The People's Government of Hebei Province. Interpretation of the implementation scheme of Zhangjiakou establishing the national demonstration city of Public Transport City. 2018. 7 May 2018 6 Novemver 2019]; Available from: http://www.hebei.gov.cn/hebei/11937442/10756595/10756620/14245361/index.html.
[45] Sun J. In: Zhangjiakou will establish the public transport city by 2020. Zhangjiakou Publish; 2018.
[46] ISO. ISO 14040:2006 Environmental management — life cycle assessment — principles and framework. 2006. p. 1–20.
[47] People's Government of Zhangjiakou. Zhangjiakou hydrogen construction plan (2019-2035). 2019.
[48] Hydrogen station planning of the ain city area of Zhangjiakou (2019-2035). 2019.
[49] Bie F. Electrolyzing capacity is limited and cost is high, which needs policy support for the electricity price. China Energy News; 2018.
[50] Wang X, et al. CO2 emission reduction effect of electric Bus Based on Energy Chain in Life Cycle. Journal of Transportation Systems Engineering and Information Technology 2019;19(1):19–25.
[51] Bai L. Research on volatility spillover effect and price forecast of China's carbon market. In: School of statistics. Shanxi University of Finance and Economics; 2019.
[52] Li F, Jiang H, Xu Z. Price fluctuation characteristics of carbon emissions rights trading in pilot provinces and cities of China based on the analysis of GARCH family model and value at risk (VaR). J Jinling Inst Technol Social Sci Ed 2019;33(3):35–40.
[53] Chen Z, et al. How will the Chinese national carbon emissions trading scheme work? The assessment of regional potential gains. Energy Pol 2020;137:111095.